

The “Hot” Science of RHIC

Status and Future

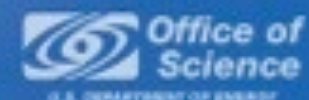
Berndt Mueller

Brookhaven National Laboratory
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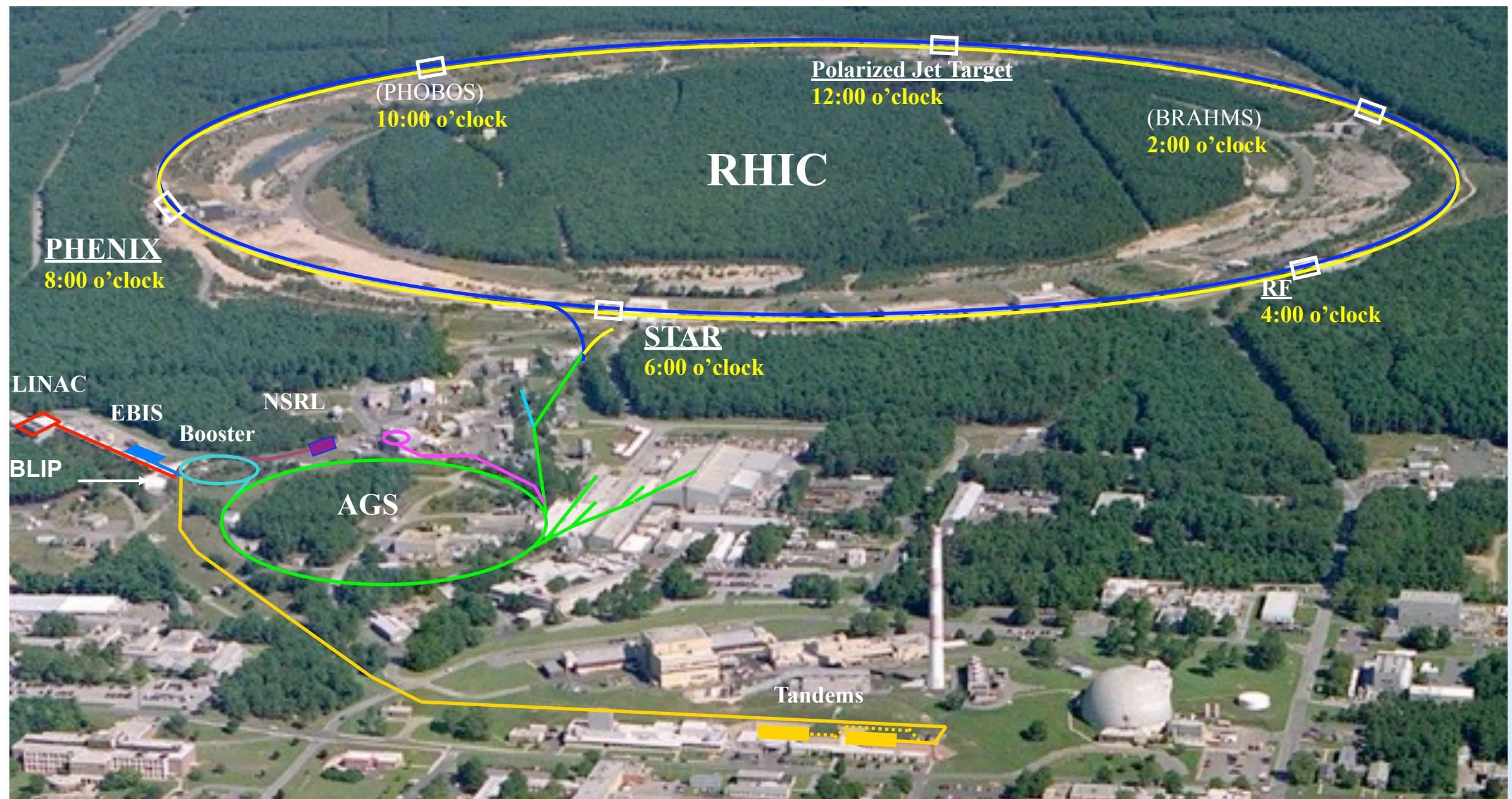
BSA Board Meeting
BNL, 29 March 2013

BROOKHAVEN
NATIONAL LABORATORY

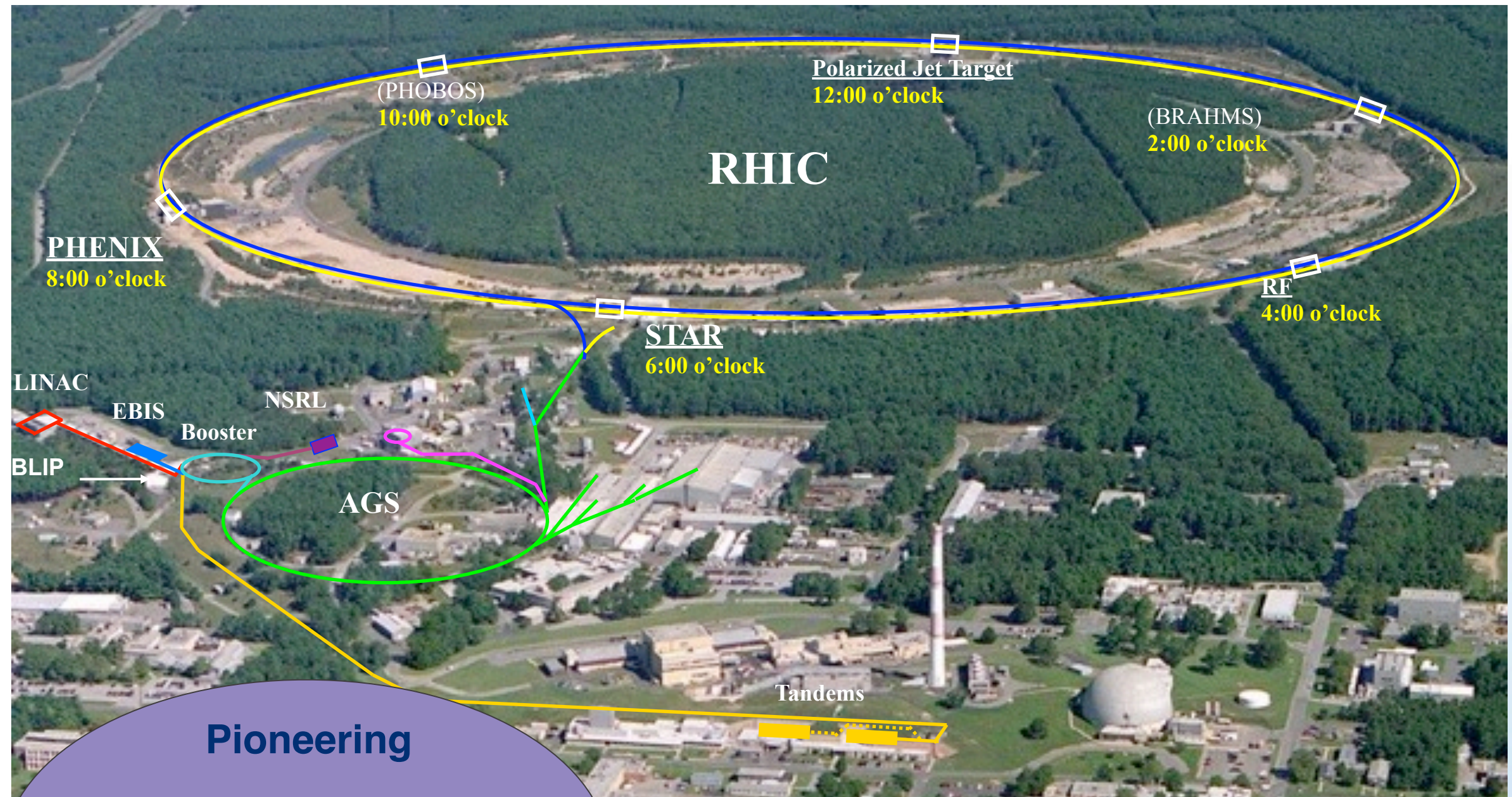
a passion for discovery



RHIC: A Discovery Machine



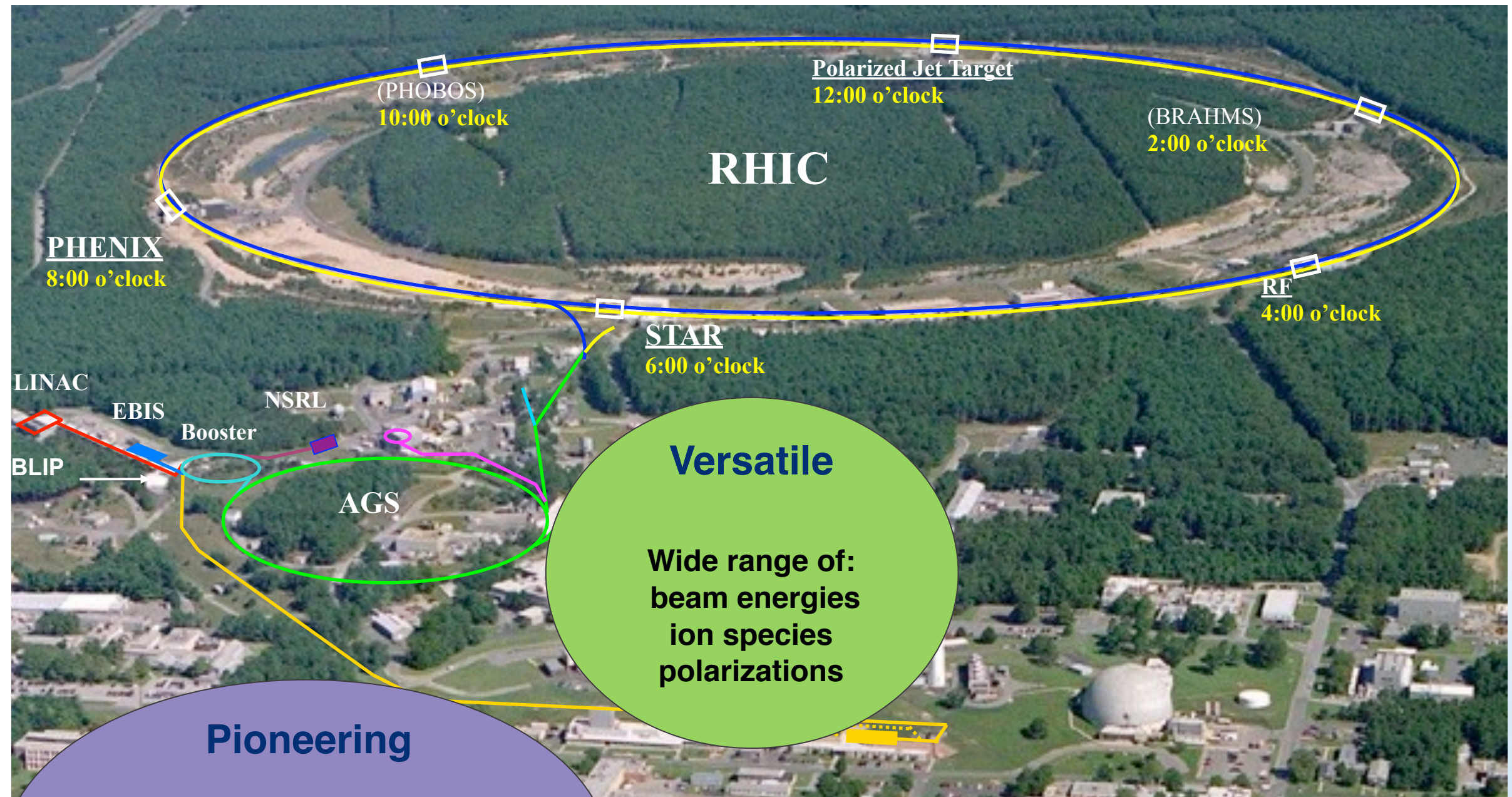
RHIC: A Discovery Machine



Pioneering

**Perfectly liquid
quark-gluon plasma;
Polarized proton collider**

RHIC: A Discovery Machine



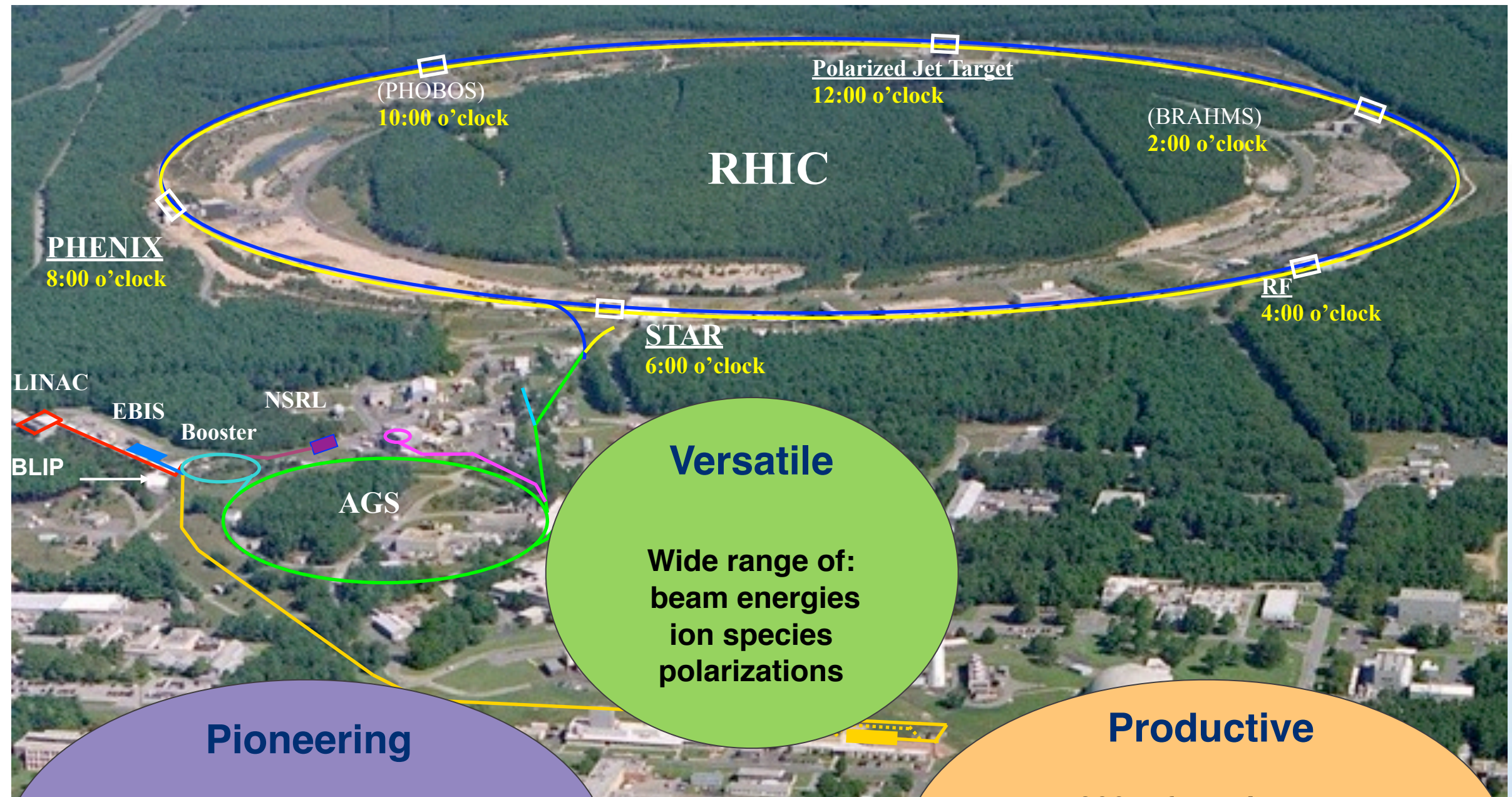
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Versatile

Wide range of:
beam energies
ion species
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RHIC: A Discovery Machine



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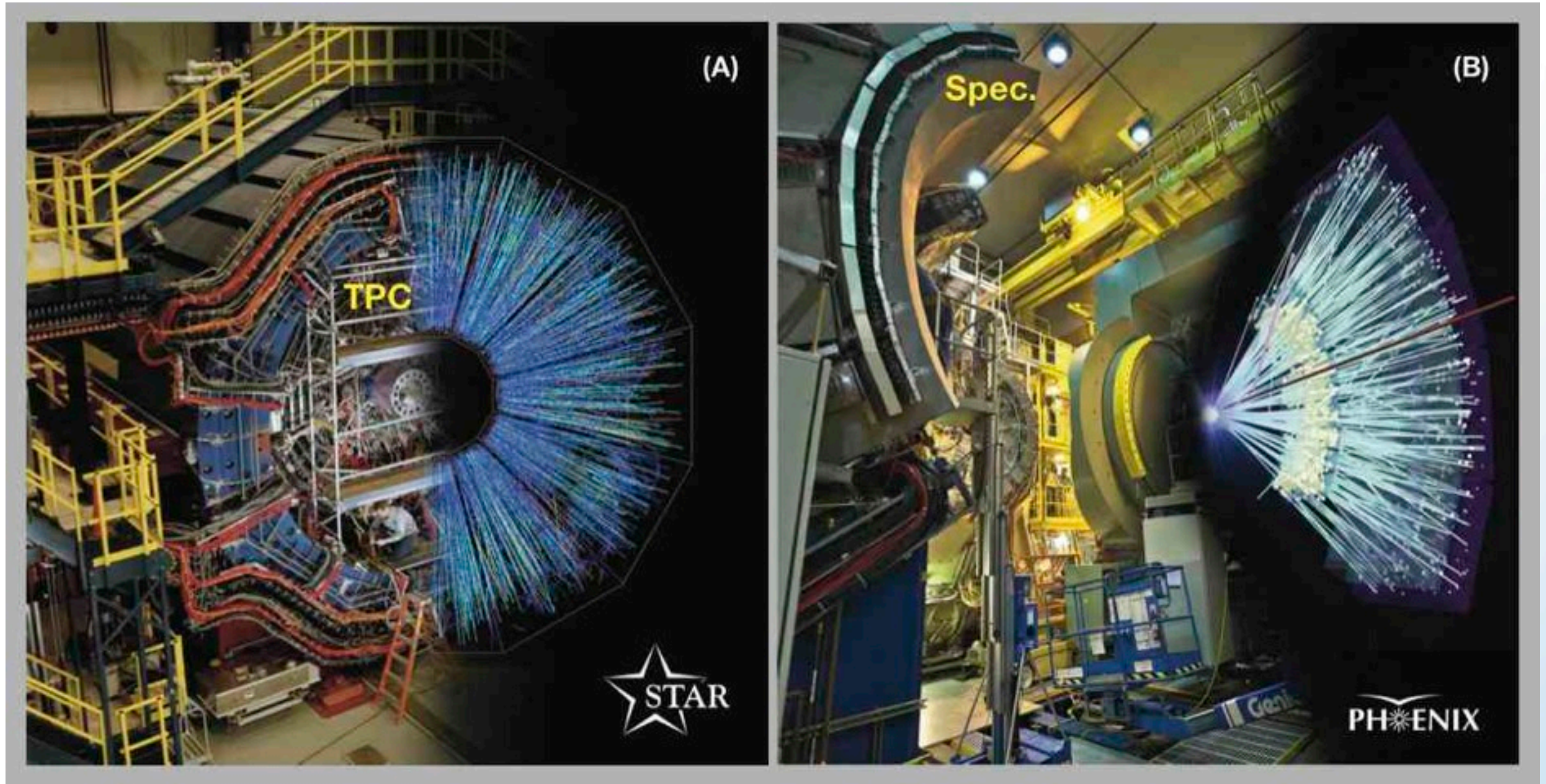
Pioneering

Perfectly liquid
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Productive

>300 refereed papers
>30k citations
>300 Ph.D.'s in 12 years
productivity still increasing

Detector Collaborations



559 collaborators from 12 countries

540 collaborators from 12 countries

RHIC explores the Phases of Nuclear Matter

LHC: High energy collider at CERN with 13.8 - 27.5 times higher beam energy: Pb+Pb, p+Pb, p+p collisions only.

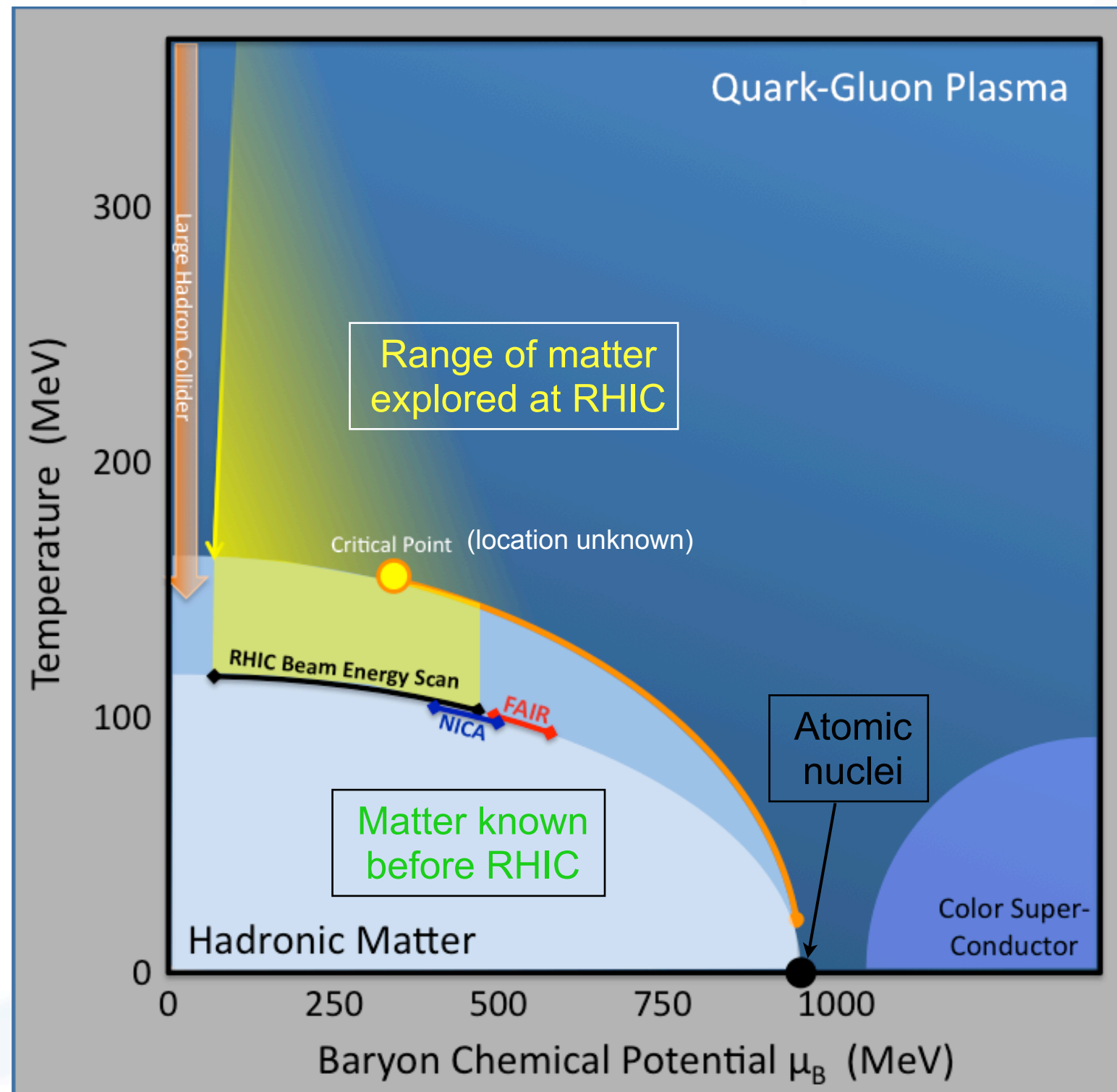
FAIR & NICA: Planned European facilities at lower energies.

RHIC: Spans largest swath of the phase diagram in preferred collider mode.

Message

RHIC is the perfect facility to explore the phases of nuclear (QCD) matter.

If RHIC did not exist, someone would have to build it (...but no one could afford it!)



Quantum Chromo-Dynamics (QCD):
Fundamental theory of nuclear or “strong” interactions

Nuclei are really complex assemblies of quarks and gluons

⇒ Nuclear matter in all its forms is known as “QCD matter”

**RHIC has pioneered the laboratory study
of condensed QCD matter**

RHIC’s results have defined a new subfield of (nuclear) physics.

*Scientists, from condensed matter physicists to string theorists,
have taken note.*

So what has RHIC discovered?

Imagine....

...heating a liquid (nuclear matter) until it turns into vapor (nucleon/hadron gas) at approximately 100 billion degrees.

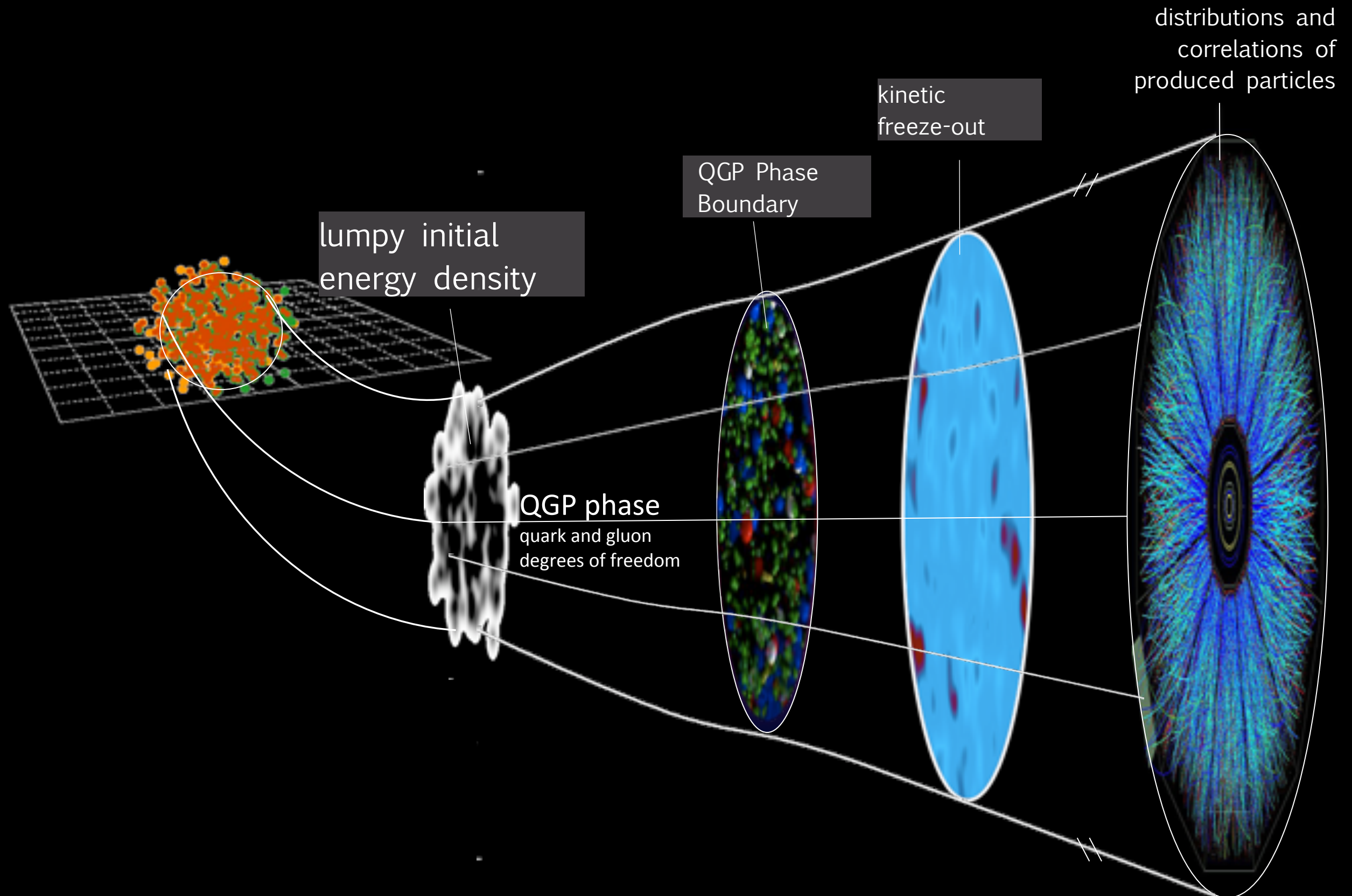
But when you heat it to 20 times this temperature (2 trillion degrees) you find that it suddenly turns into a **liquid** again, in fact, into the **most perfect liquid** ever observed.

How is this possible? [We don't really know.]

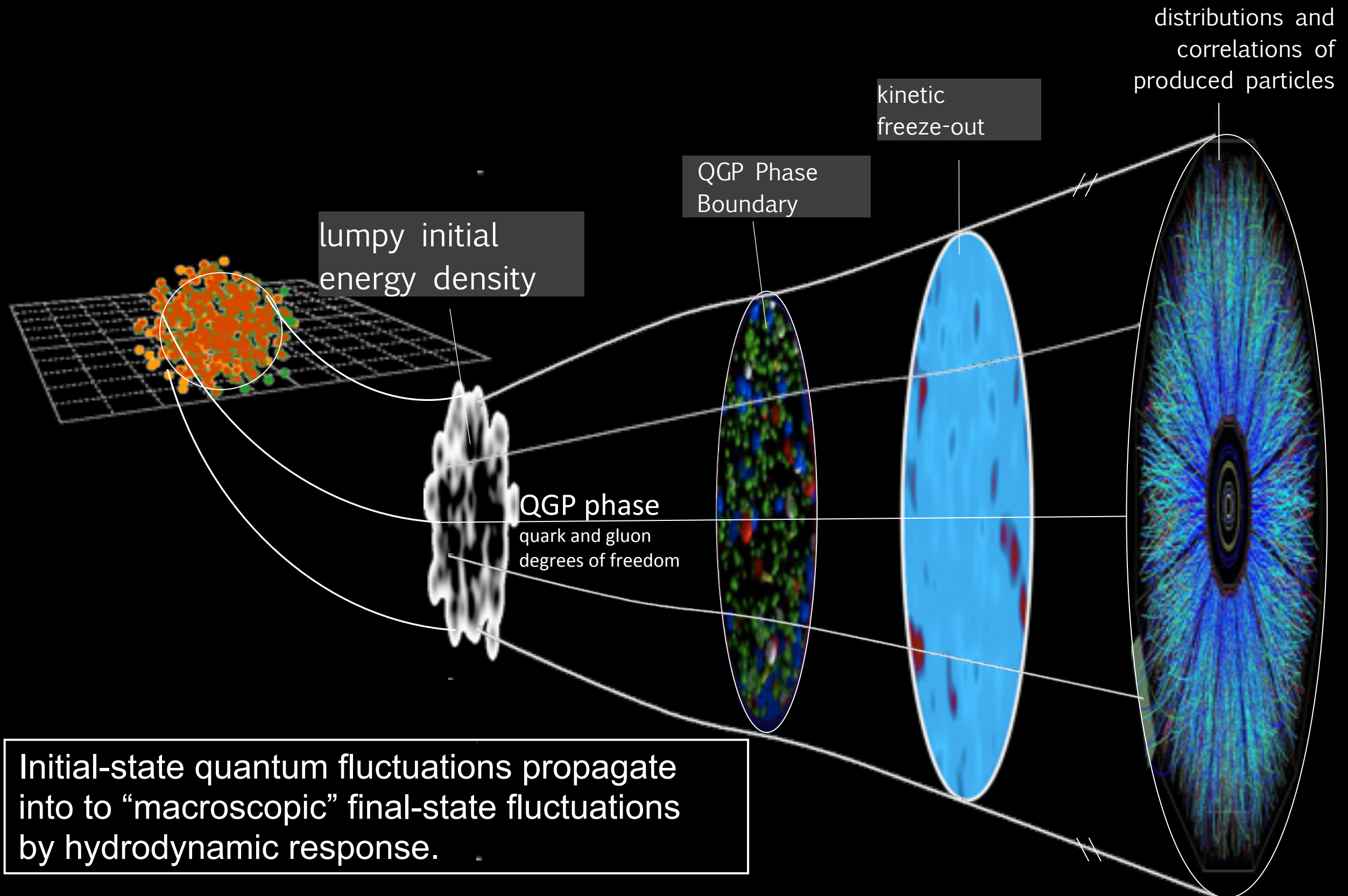
What happens at even higher temperatures? [We know.]

Where is the perfect liquid formed? [We almost know.]

RHIC has pioneered the lab study of condensed QCD Matter



RHIC has pioneered the lab study of condensed QCD Matter



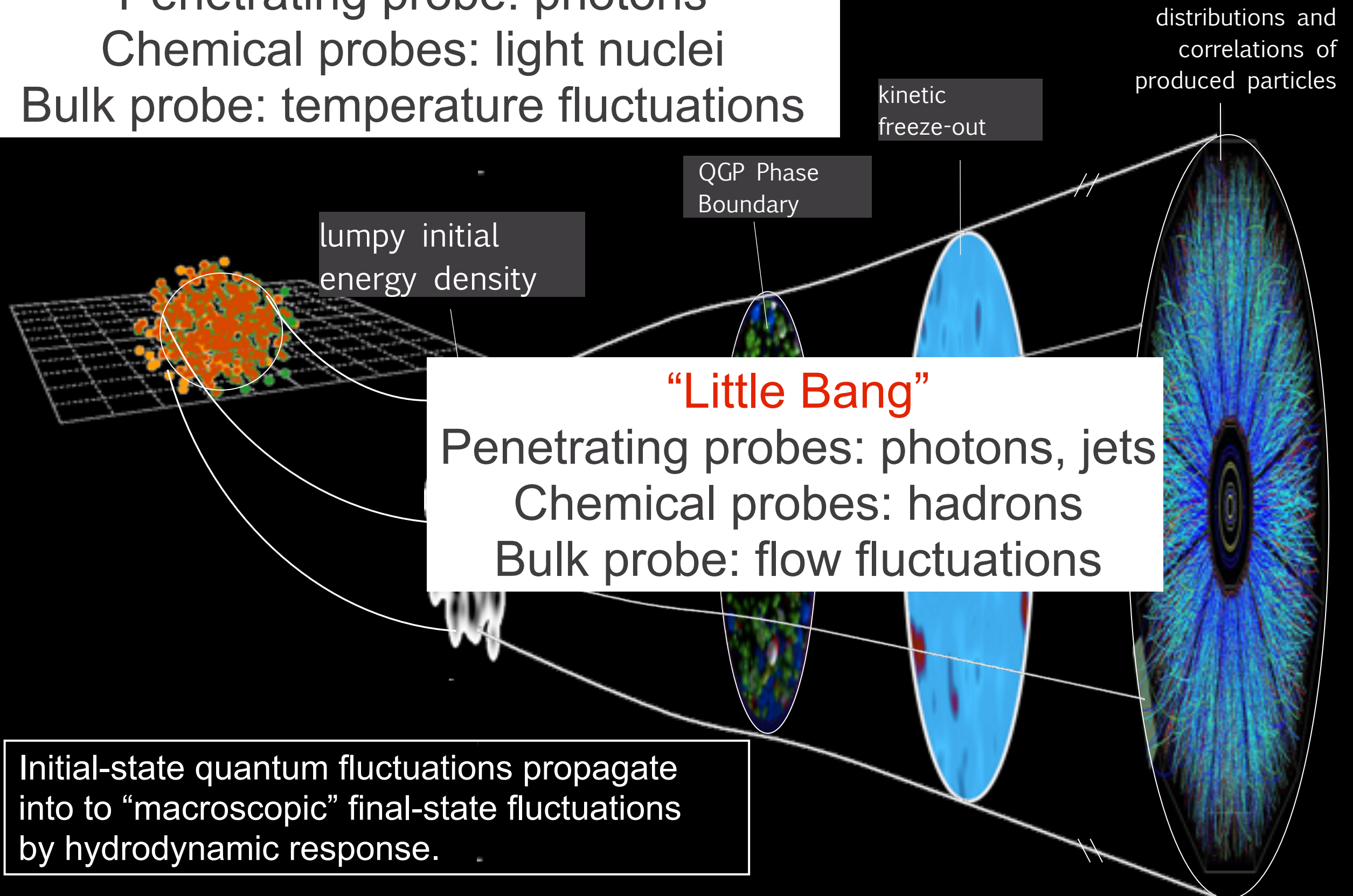
RHIC has pioneered the lab study of condensed QCD Matter

“Big Bang”

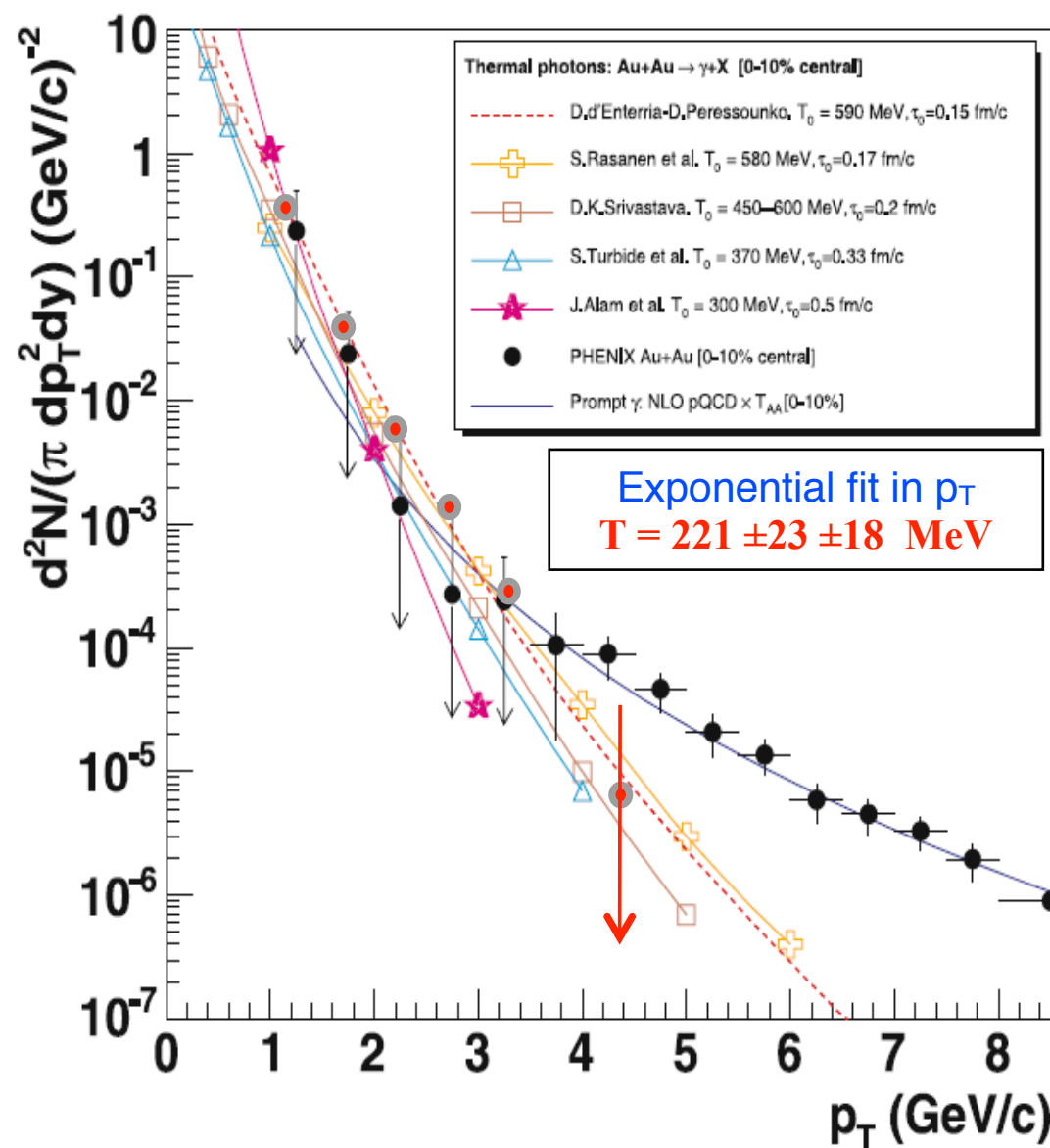
Penetrating probe: photons

Chemical probes: light nuclei

Bulk probe: temperature fluctuations

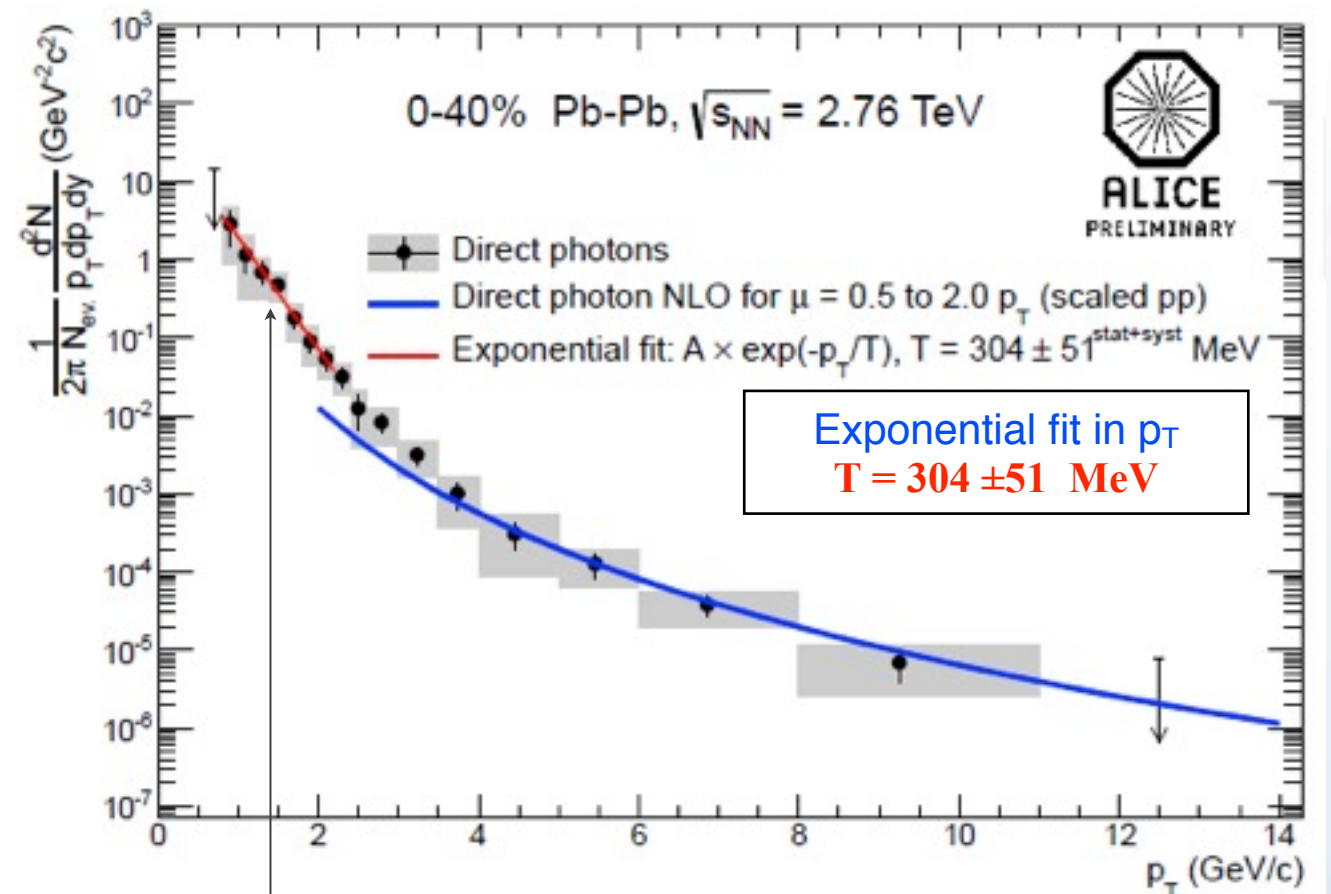


A “Guinness” record temperature



Corresponds to initial temperature:
 $T_{\text{init}} \geq 300$ MeV

$T_{\text{init}} \geq 4$ trillion degrees



New **record “temperature”** measured at LHC:

$$T_{\text{LHC}} = 1.37 T_{\text{RHIC}}$$

$T_{\text{init}} \geq 5.5$ trillion degrees

Measuring “fluidity”

Viscosity (η) measures how well a fluid responds to variations in the uniformity of flow.

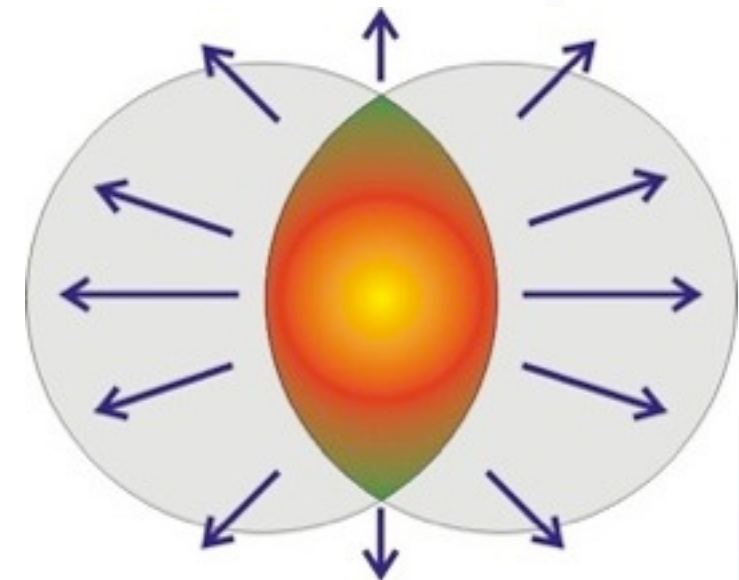
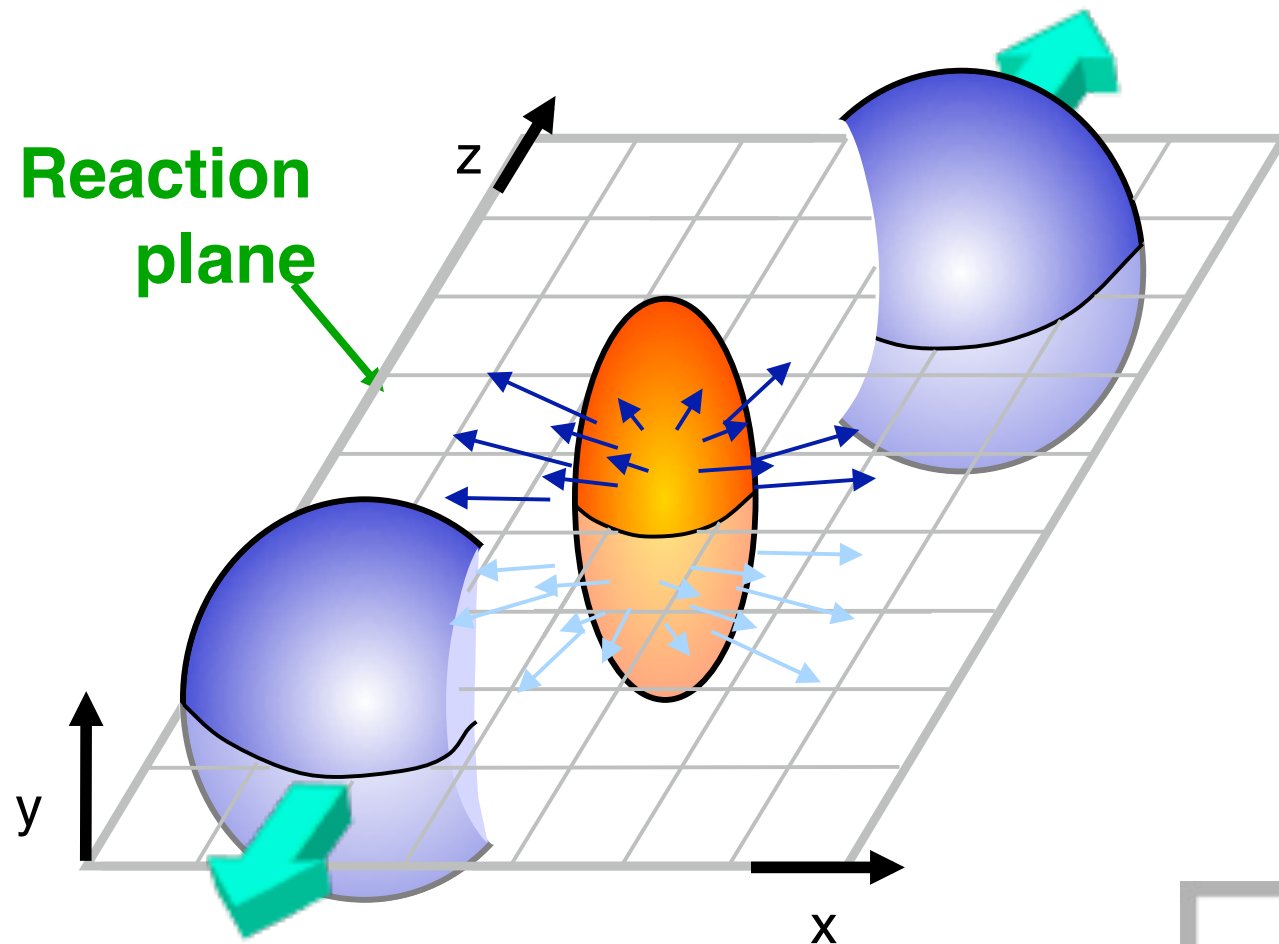
Quantum physics dictates that viscosity cannot be zero.

A dimensionless measure of perfect fluidity is η/s , which cannot be less than $1/4\pi \approx 0.08$.

The RHIC data indicate that QCD matter has $\eta/s \approx 0.12$.

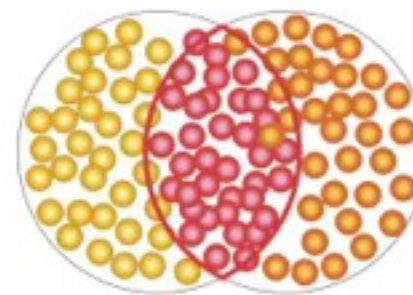
No other liquid is known with such a low value.

Anisotropic flow

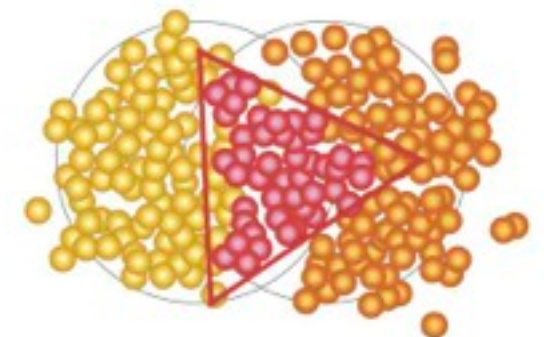


Only matter in the overlap area gets compressed and heated

$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n v_n(p_T, \eta) \cos n(\phi - \psi_n(p_T, \eta)) \right)$$



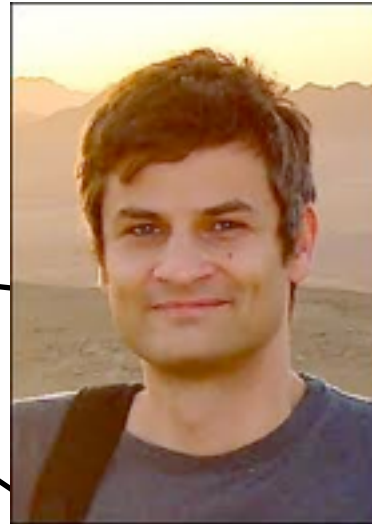
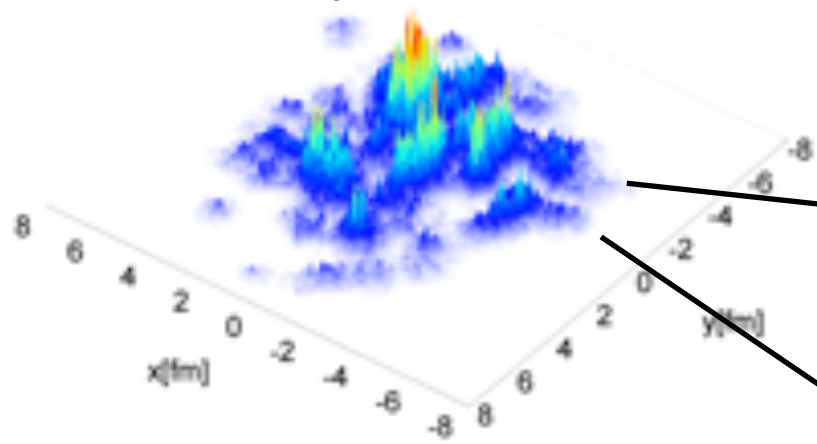
Elliptic Flow



Triangular Flow

QCD Matter at RHIC is most “perfect”

Initial density distribution

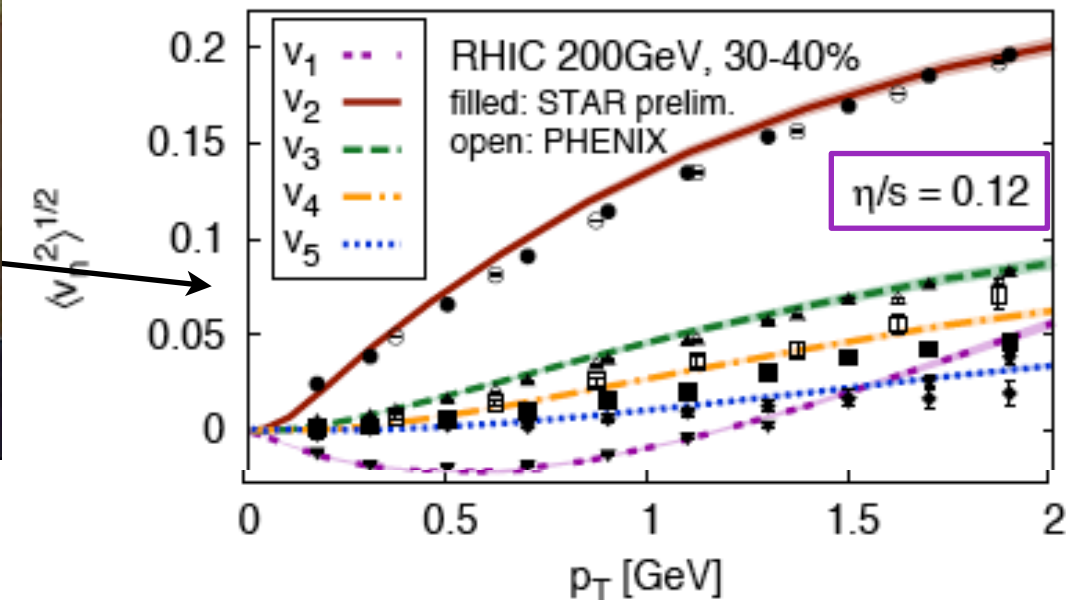


B. Schenke (BNL - Goldhaber Fellow)

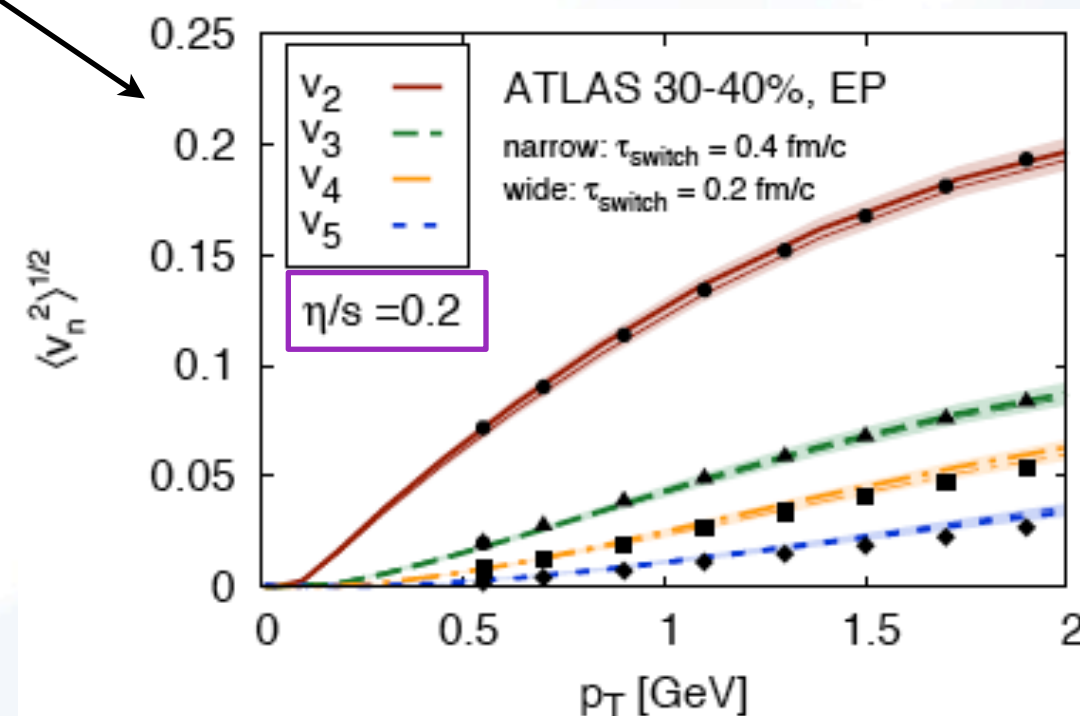
$$(\eta/s)_{\text{RHIC}} \approx 0.6 (\eta/s)_{\text{LHC}}$$

A study of the opacity of the matter to energetic quarks (jets) confirms this conclusion:

QCD matter at RHIC is less transparent by the same factor 0.6.



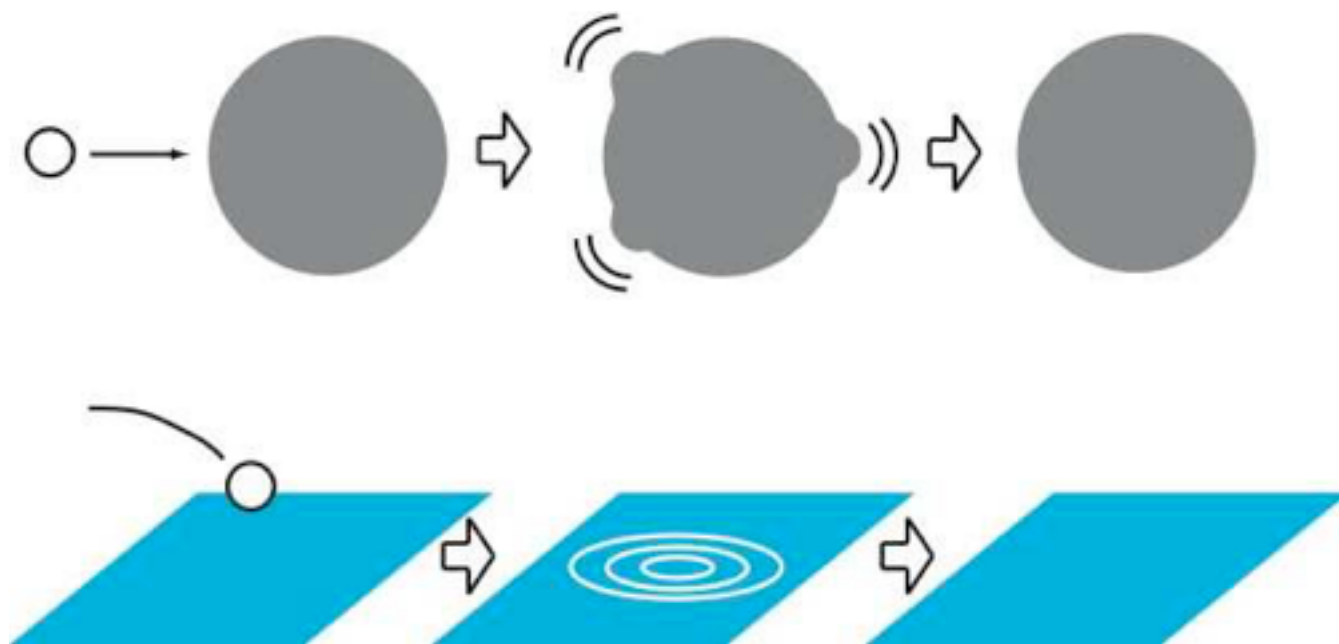
RHIC



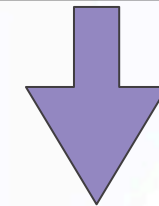
LHC

The Black Hole connection

Dynamics of hot QCD matter can be mathematically mapped on black hole dynamics in 4 dimensions



BH swallowing matter



Perfect fluid
hydrodynamics

Formation of hot QCD matter at RHIC is similar to formation of a black hole, tied to information loss.

The Black Hole connection II

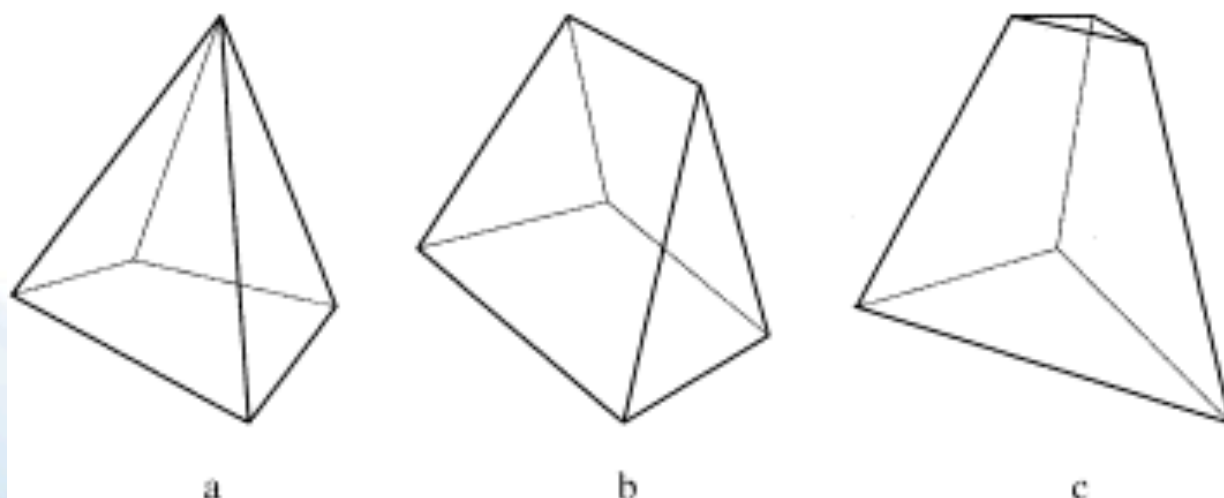
BH horizon acts like a perfect liquid;
BH destroys information as fast as possible. Why and how?

Study the dynamics of elements of empty space:
Strings in string theory; or polyhedra in loop quantum gravity



Dynamics of tetrahedron
is regular and periodic

Chris Coleman-Smith
(Duke grad. student)



Dynamics of pentahedron
is irregular and chaotic

**RHIC explores the most perfectly liquid,
most opaque form of the quark-gluon plasma.**

**This discovery connects to the deepest
properties of space and time**

**New upgrades
will make RHIC even more powerful:**

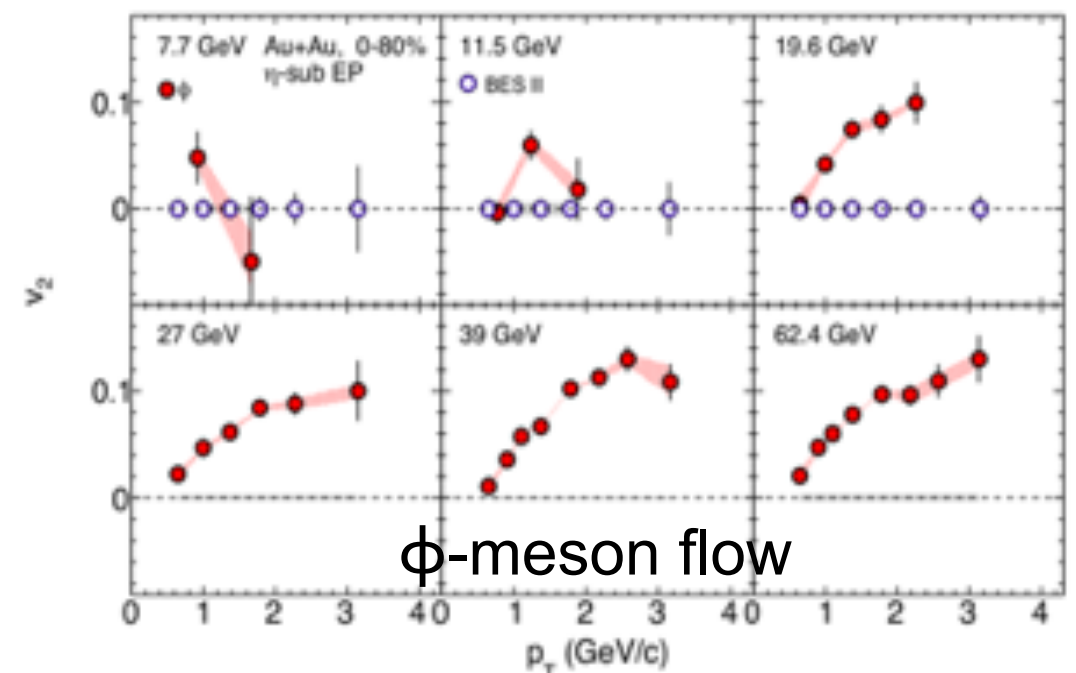
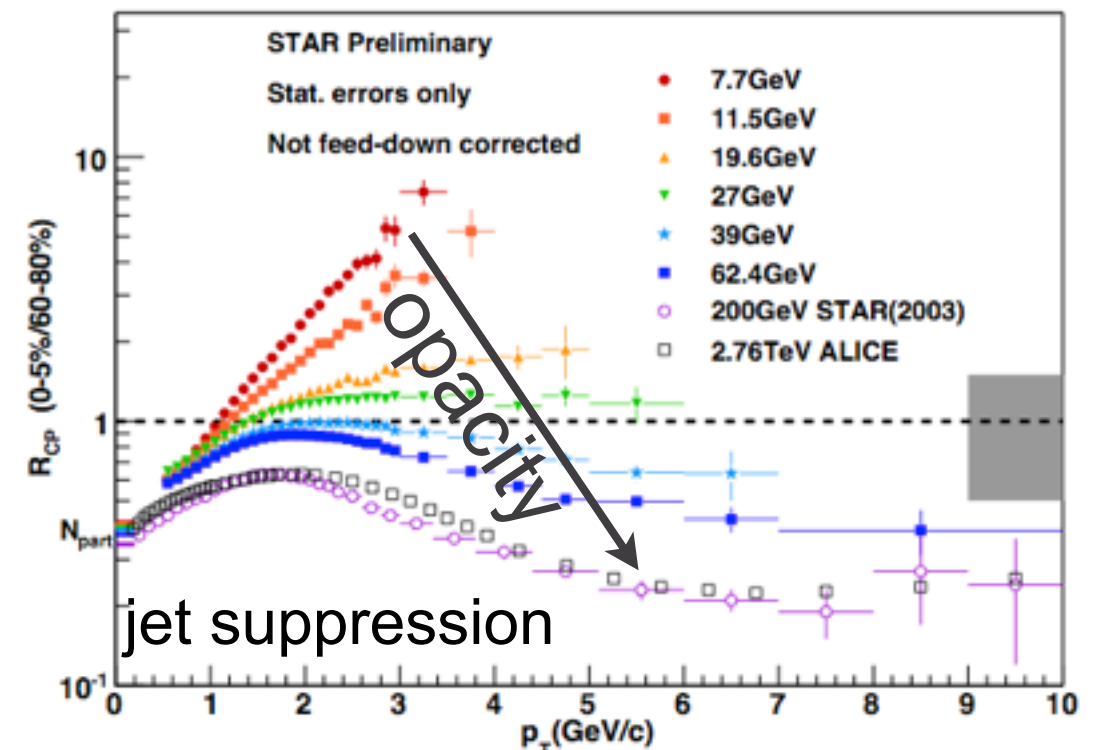
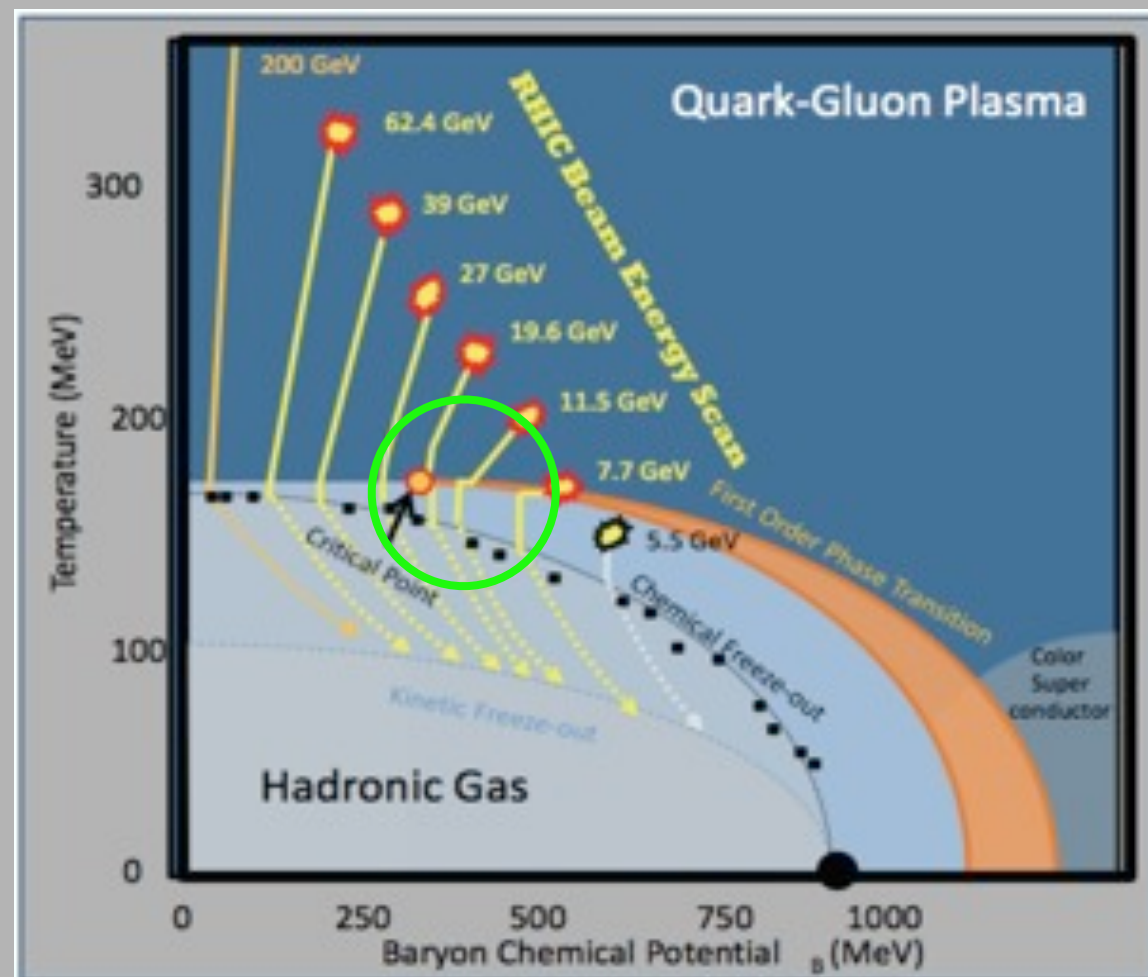
Vertex detectors will identify heavy quarks

Electron cooling will increase luminosity

Where is the “Perfect” Liquid formed?

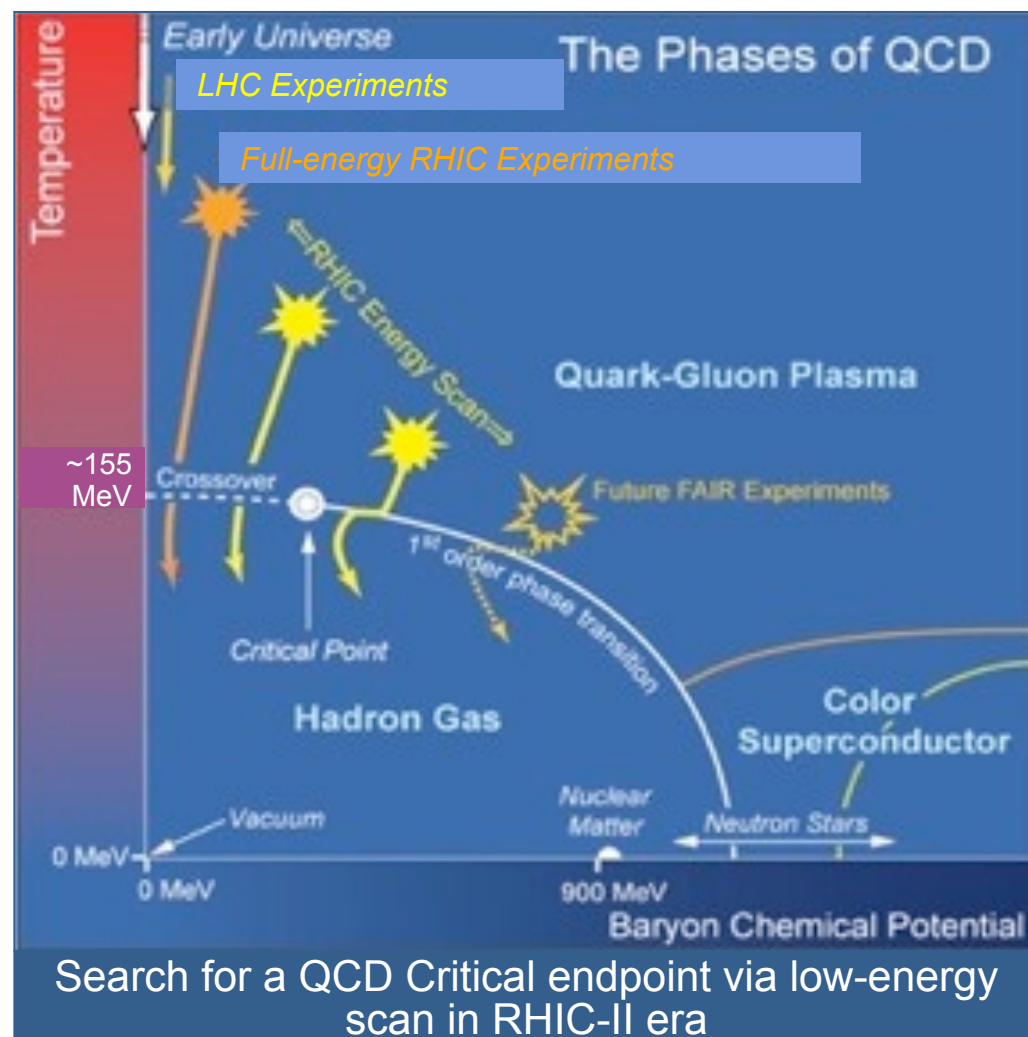
Probing the QCD Phase-Diagram

- RHIC Beam Energy Scan: use beam energy as control parameter to vary initial temperature and chemical potential
- Beam energy range in area of relevance is unique to RHIC!
- BES-II will deliver precision required to search for signatures of the CEP



RHIC: Science Goals for the Next Decade

Quantify properties of the QGP by measuring **heavy quarks** and features of the QCD phase diagram as functions of temperature and net quark density.

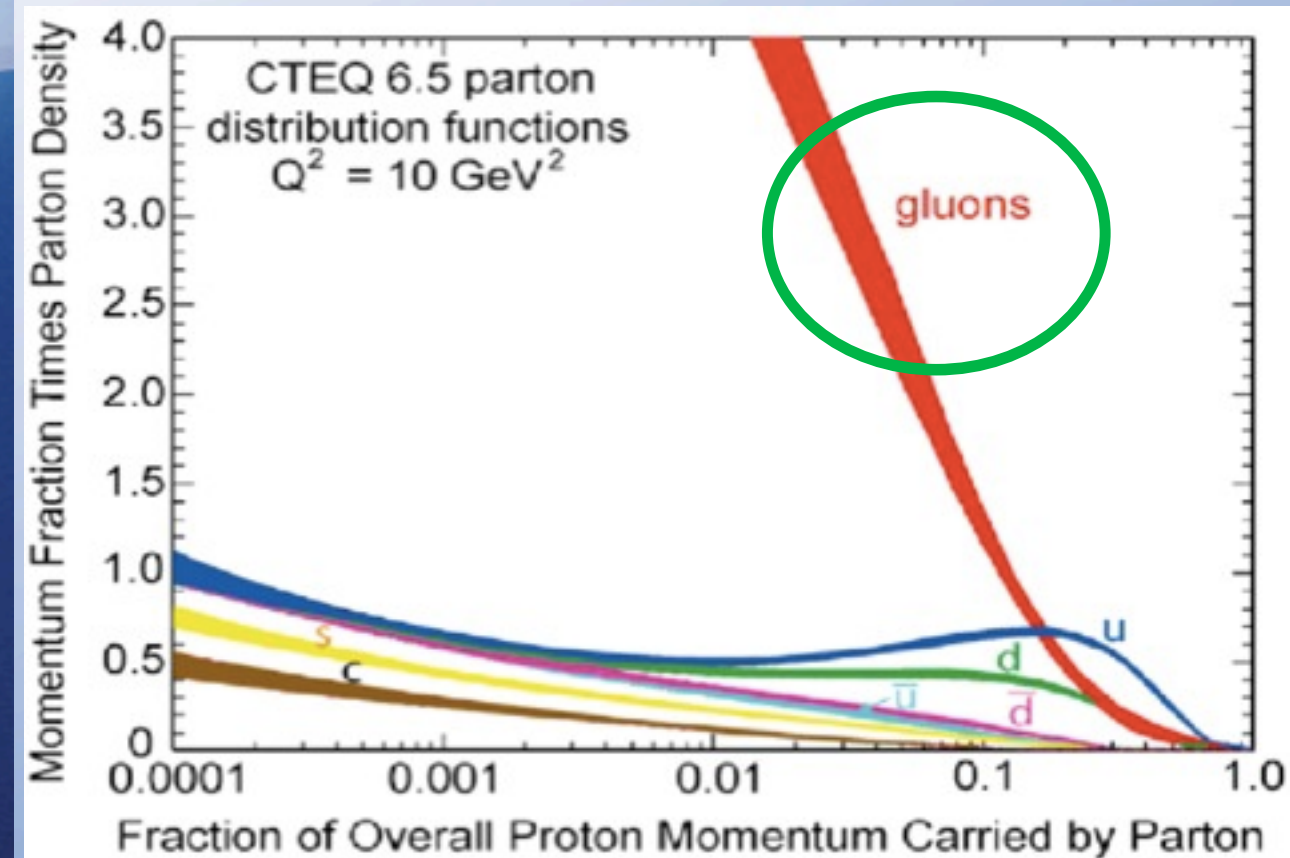
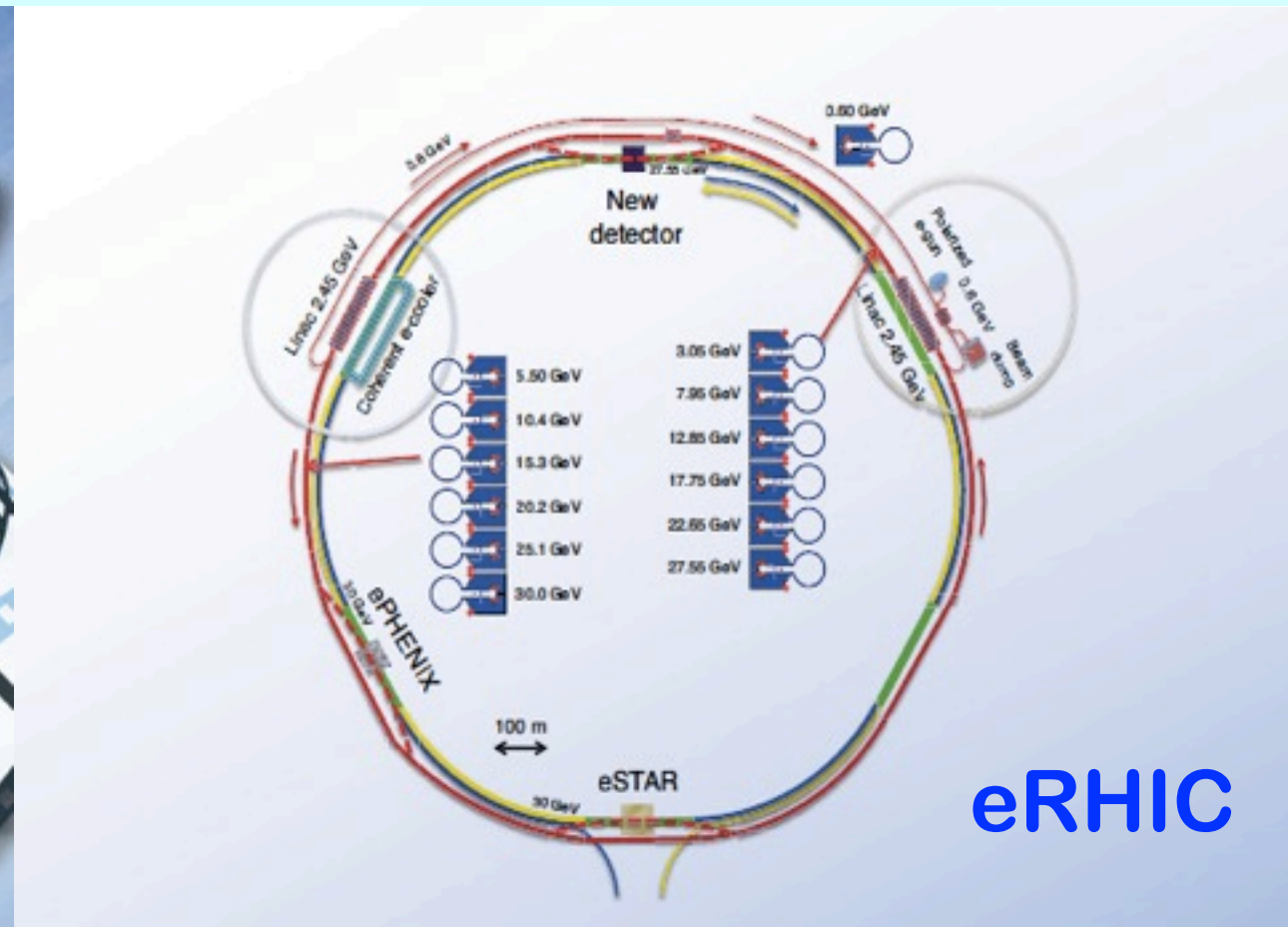
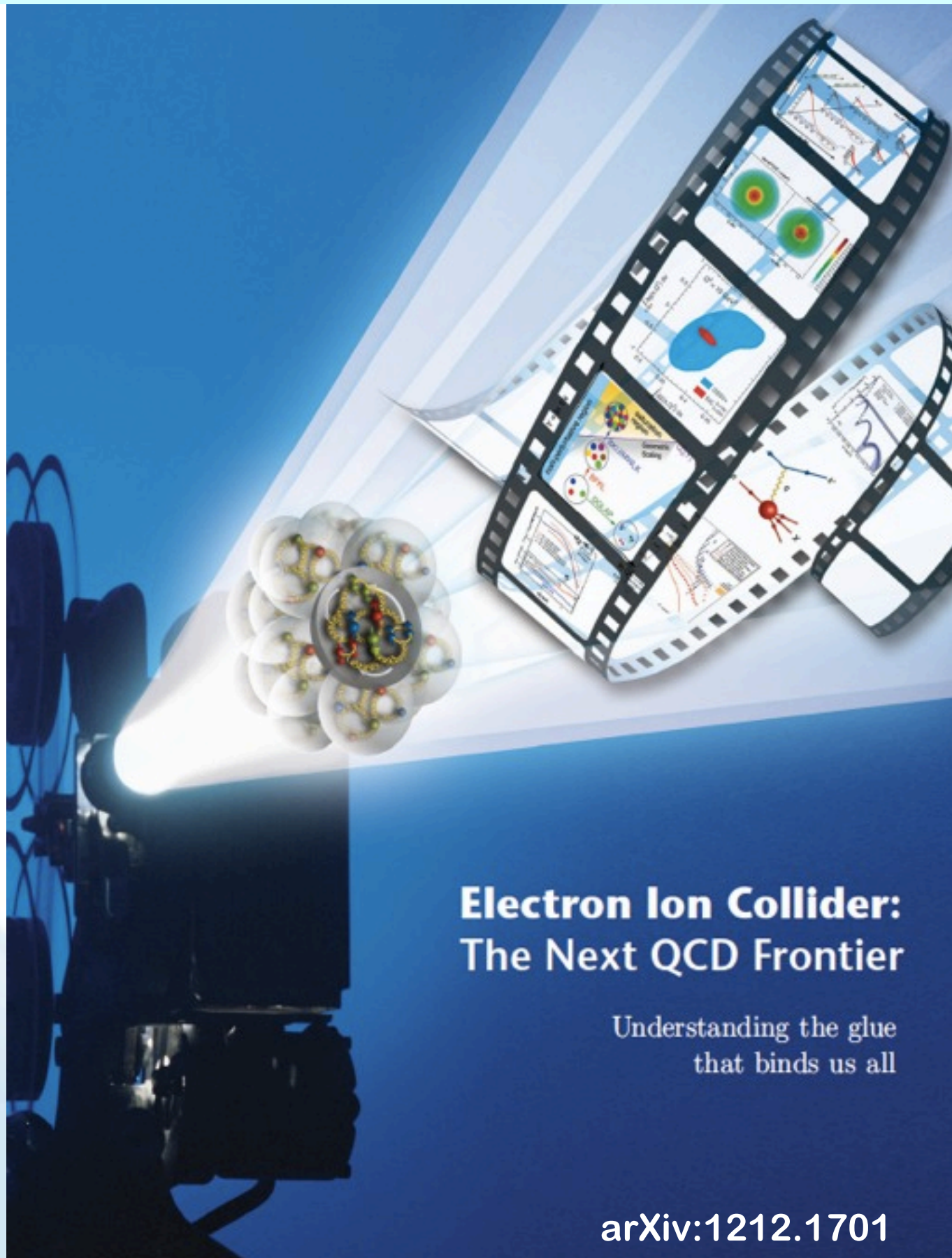


Exploit new discovery potential in searches for a **QCD critical point** and for the nature and influence of quantum fluctuations in initial densities and gluon vacuum excitations.

Continue explorations of the role of **soft gluons in cold nuclear matter** (gluon saturation, gluon and sea quark contributions to proton spin). Precursor to eRHIC program.

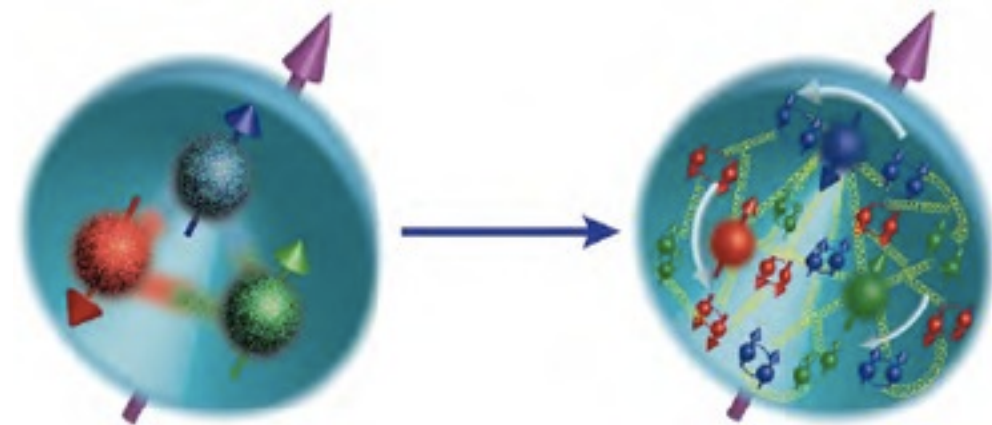
Caveat: Budget constraints make a deliberate execution of a decadal program of scientific inquiry challenging

EIC: An electron microscope for QCD matter

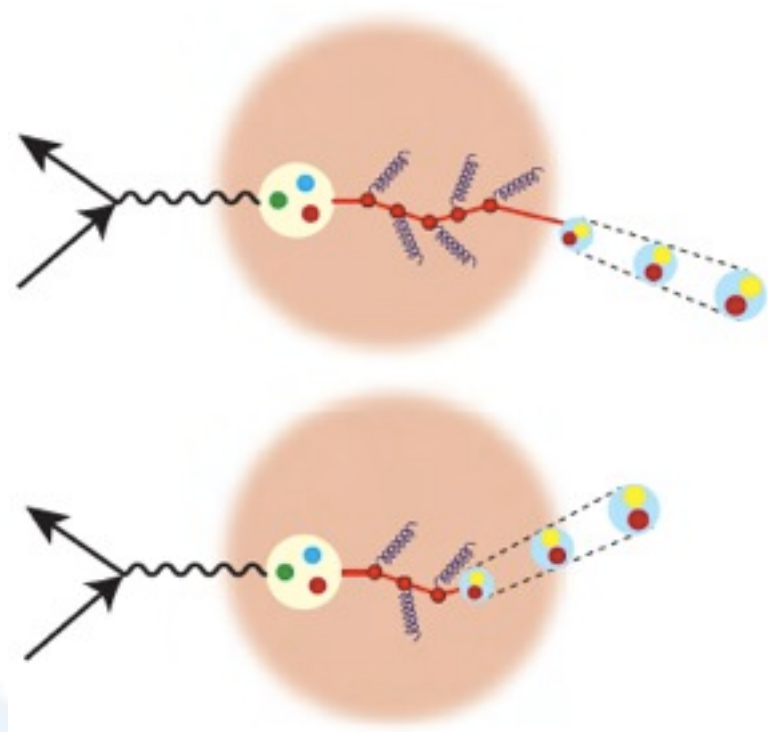


eRHIC will be a QCD laboratory

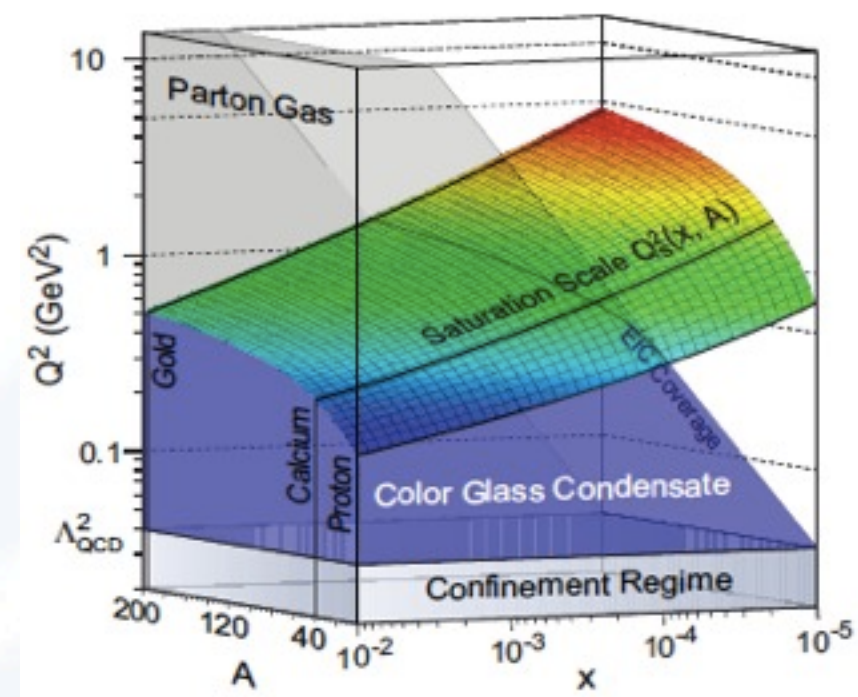
Gluon structure of proton



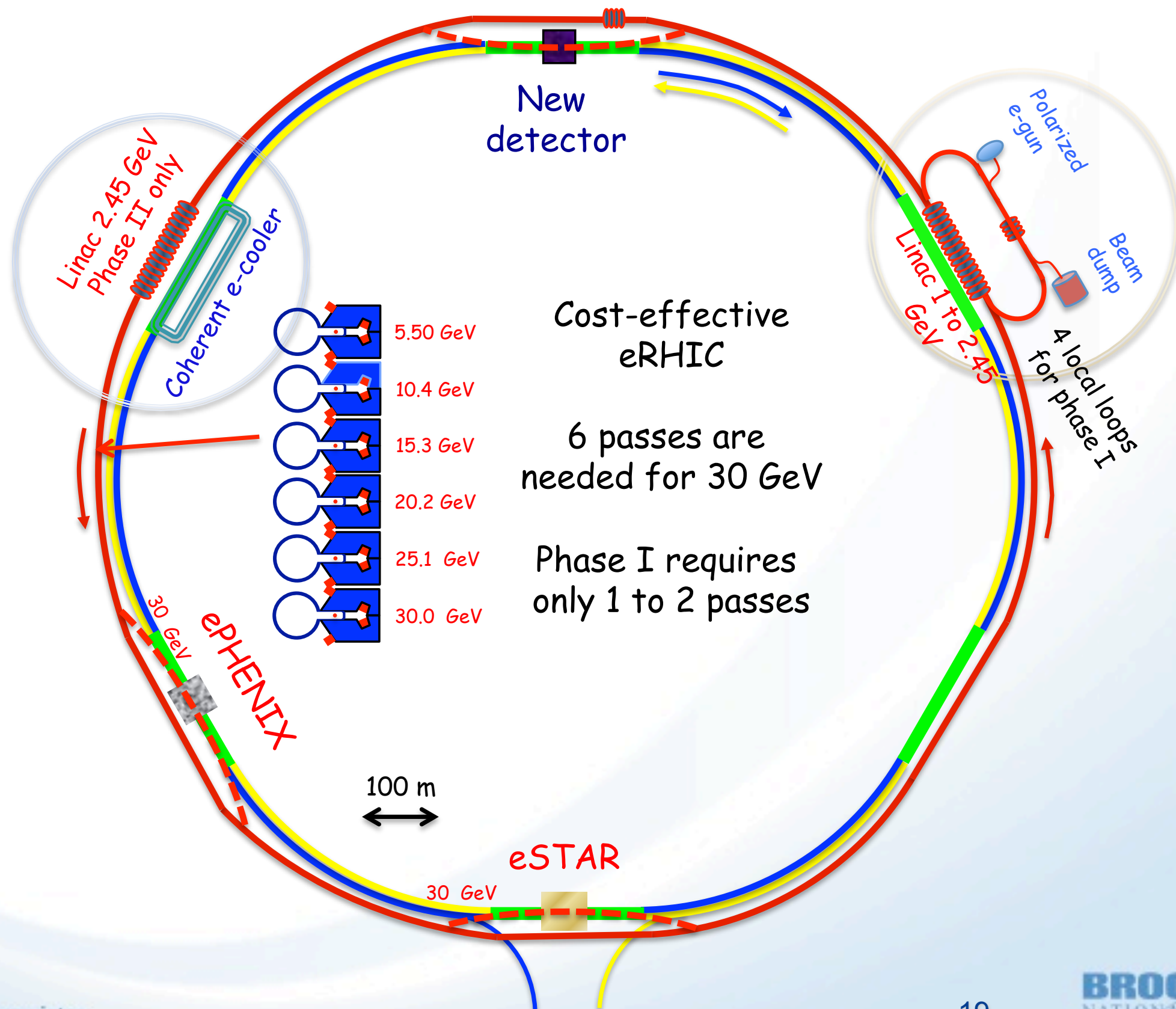
Microscopic processes studied in bulk at RHIC



High density phase of gluon matter (CGC)



From RHIC to e-RHIC



Summary

- If RHIC did not exist, it would need to be built
- \$2B infrastructure uniquely capable to explore QCD matter in the perfect liquid domain
- RHIC sits at the sweet spot: most liquid & opaque QGP
- The discovery potential of RHIC is undiminished
- RHIC-2 exists now -- on track to RHIC-3 in 2017/18
- RHIC's path toward eRHIC is clearly delineated and provides for a cost-effective realization of the EIC
- We are developing the technical and scientific case for eRHIC to be presented at the next long range plan
- RHIC & eRHIC can ensure U.S. preeminence in research on QCD for the next 2-3 decades